Evaluation of Turbulence-Closure Schemes for the Coastal Ocean

Dan Kelley
Department of Oceanography
Dalhousie University
Halifax, NS, Canada B3H 4J1
phone: (902) 494-1694   fax: (902) 494-2885 email: Dan.Kelley@dal.ca

David Hebert
Graduate School of Oceanography
University of Rhode Island
Narragansett, RI 02882-1197
phone: (401) 874-6610   fax: (401) 874-6728   email: hebert@gso.uri.edu

LONG-TERM GOALS

We wish to understand the dynamics of small-scale mixing processes in the ocean (e.g. turbulence, intrusions, and convection) and to determine how to parameterize their fluxes for use in larger-scale numerical models and in theory.

OBJECTIVES

Our goal is to test whether ocean mixing is described adequately by the sort of turbulence-closure schemes that are increasingly popular in numerical models of the coastal ocean. Several mixing schemes will be examined (e.g., the K-profile and Mellor-Yamada parameterizations). Our focus will be on shear-induced mixing, and we will make heavy use of observations of tide-generated mixing on Georges Bank. A data-assimilative approach, blending observation and prediction in an optimal way, will be used to shed light on the strengths and weaknesses of the mixing parameterizations. We will also address the relevance of various aspects of the models (e.g. advection/mixing of turbulence, temporal variations of C_D, etc.) in the context of the physics of ocean mixing.

APPROACH

We have undertaken a suite of tests of turbulence closure schemes using a set of oceanographic measurements of velocity and turbulent dissipation rate collected by one of us on Georges Bank during Phase I of the U.S. Northwest Atlantic/Georges Bank GLOBEC project (Burgett et al. 1996). The observations were made at two anchor stations, during two cruises. One station was in a shallow (45 m depth) well-mixed region. The other was in deeper water where stratification was just starting to develop during the first cruise and was established by the time of the second cruise. At each site, microstructure measurements of mixing were made using the tethered free-falling instrument EPSONDE (Oakey 1988), and ship-based velocity measurements were made with three RDI Acoustic Doppler current profilers.

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14. ABSTRACT

We wish to understand the dynamics of small-scale mixing processes in the ocean (e.g. turbulence, intrusions, and convection) and to determine how to parameterize their fluxes for use in larger-scale numerical models and in theory.

15. SUBJECT TERMS

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The currents at these sites are dominated by the M_2 tide, and so is the variation of ε, the turbulent kinetic energy dissipation rate. The latter also has a significant component at twice the M_2 frequency. There are several possible explanations for this variation in ε, such as turbulence being generated in mid-column by the square of the tidal shear, or turbulence resulting from bottom stresses that are proportional to the square of the current speed (Burgett et al. 2001). Terms for both effects are present in today's turbulence-closure schemes, so that models should be capable of explaining the observations qualitatively. Still, only quantitative comparison, across a range of model parameters, can justify reliance on the models to mimic the physical processes in a generally valid way. Such quantitative comparisons are most easily carried out using data-assimilative techniques. Data assimilation compares predictions and observations in a systematic and optimal way, recognizing both the dynamical constraints of the models and the experimental uncertainties of disparate observations.

We use two 1-D tidal models in this study, each of which incorporates second-order turbulence closure schemes as well as simpler mixing schemes. To date we have focussed on the NUBBLE code (Naimie 1996), which has been applied in related projects. More recently we have joined community-modeling efforts by using the GOTM code (Burchard and Petersen 1999; also see http://gotm.net). A strength of GOTM is that it is in continual development, keeping abreast with new parameterizations (e.g. of internal waves, Langmuir circulation, etc.).

Our assimilations are designed to fit for "control variables" that represent the pressure forcing terms and various model parameters. The turbulence-closure schemes under study have many adjustable parameters, and our early tests revealed that it would be impractical to try to assimilate for all of them. Therefore, we chose to focus on what is really the core parameter for tidal mixing -- the parameters that relate the bottom drag to near-bottom flow. (In the literature, and in our models, there are two related ways of representing the bottom drag. One is in terms of a bottom drag coefficient C_D and the other is in terms of a bottom roughness length; since these parameters are related algebraically in the models, we will simplify this report by referring to C_D.) The value of C_D is commonly tuned in numerical models of a given region, usually taking it to be constant across space and time. This is problematic since laboratory experiments reveal that C_D varies with the bottom type (e.g., depending on the presence and orientation of ripples, etc.) and bottom type certainly varies with location and perhaps varies with time also, for example, if ripples vary through the tidal cycle (Soulsby 1990). Spurious results could arise from the assumption of a spatially- and temporally-constant drag coefficient. For example, model tuning based on tidal wave propagation will be biased to regions with the swiftest currents, since column-integrated dissipation is proportional to $C_D U^3$, where U is the near-bottom speed. Therefore, adjusting C_D to match spatially-averaged mixing may yield inaccurate results locally.

Another issue is that detailed studies of bedforms in movable sediments indicate complex, and as yet not well understood, temporal variations with varying flow regimes. For example, a recent Dalhousie PhD study (Smyth and Hay 2001) has shown that high wave conditions tend to flatten bedforms. Given the above-stated relationship of ε to C_D and water speed, the tendency is thus to reduce ε under exactly the conditions expected to favor enhanced mixing. Smyth's results were for wave-induced mixing in a nearshore environment, and it is not clear whether the same effect might hold for tidal flows. Still, there are indications of strong variation in soft-sediment bottom roughness over the tidal cycle: Soulsby (1990) reviews evidence of bottom roughness varying tidally by as much as a factor of 10. If such a pronounced variation is a general result for flow over movable sediments, then it casts great doubts on all inferences based on constant-C_D models.

In summary, we have reasons to think C_D might vary through the course of a tide, and indications that the variation could be significant. However, there are important uncertainties about the nature of the variation, e.g., whether it relates to flow speed, flow direction, or variations in either. It is also unclear whether this is a universal result for flow over movable sediments, or a special case that applies only after some non-dimensional threshold is crossed. Motivated by such first-order questions about something that modelers often taken as a basic parameter, we have focussed during the report period on the temporal dependence of C_D.

WORK COMPLETED

Our study involves using two models (NUBBLE and GOTM), two ways of interpolating observations (in frequency and in time), and two ways of weighting the model-observation misfit (with $\log(\varepsilon)$ and with ε). A straightforward scheme has been devised to break this analysis up into standard "runs", and we are well underway in the execution of our work plan. Many of the NUBBLE-based runs have been done. The GOTM-based work is only starting, and is being done by Daniel Bourgault, a newly-hired Dalhousie postdoctoral researcher working with one of us.

In our last report we discussed runs in which C_D was adjusted to fit the ADCP velocity signal, or some combination of velocity and dissipation rate. These provide a foundation from which we have moved on to a study of time-dependent C_D. We have explored the C_D dependence in three ways: as function of (tidally-varying) velocity; as a mean plus an M2 component; and as a mean plus M2 component plus a twice-M2 component. In the next section we report on the second scenario, which we have investigated most closely so far.

RESULTS

Adjusting the harmonic coefficients of the pressure dependent terms yields a close match between observation and prediction (Fig. 1). As reported last year, the velocity misfit provides a much weaker constraint on C_D than does the combination of velocity and dissipation-rate misfit. Another key result is that the models capture the phase of temporal variations of dissipation-rate better than they capture the vertical variation. A remaining issue, under consideration at the moment, is that the model represents mixing as occurring through a wider range of the water column than the observations reveal.
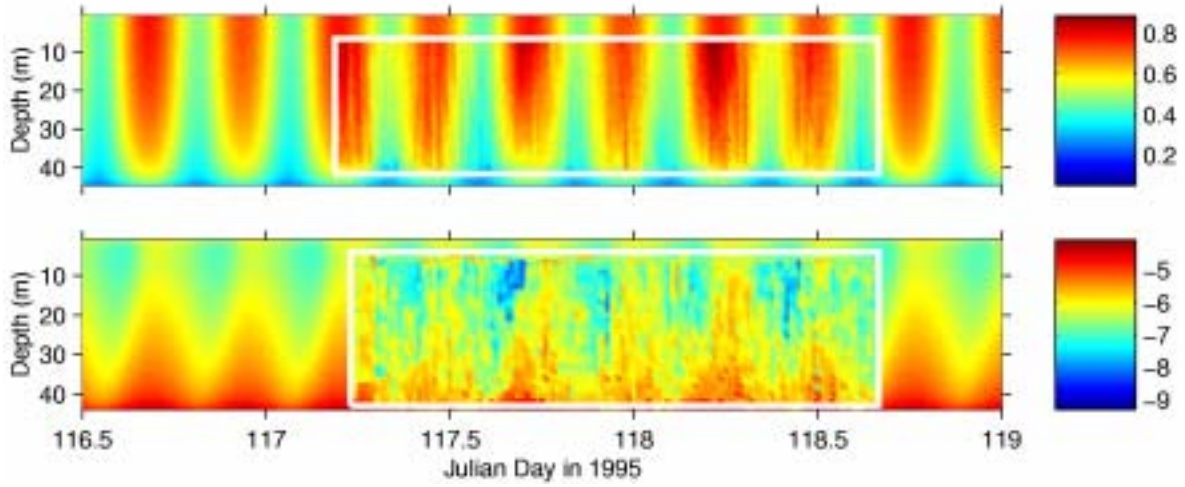
Figure 1. Observations and model predictions of current speed (m/s, upper panel) and the logarithm of dissipation rate (W/kg) for the first occupation of the shallow site on Georges Bank. The start/end of the interval represents the model output, and the insets show the observations. This particular assimilation run (one of dozens) minimizes misfits in velocity only, ignoring misfits in the dissipation rate signal. For velocity, the misfit is very low, as indicated by the smooth blending between the inset and the rest of the figure. The misfit in the dissipation rate is more pronounced. Although the semi-diurnal signal is recovered well, the depth dependence is not. This pattern is consistent across many of our simulations, suggesting a flaw in the turbulence closure schemes under study.
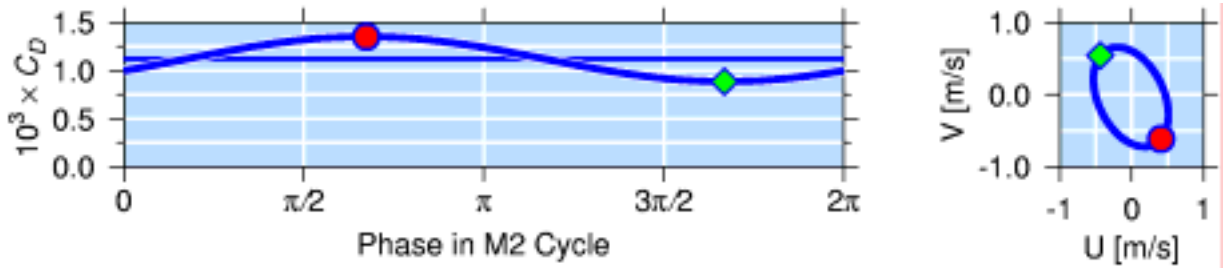

Figure 2. Temporal variation in drag coefficient C_D from a simulation in which C_D was represented with a mean component plus an M2 variation. The left panel indicates that C_D varies by about 20 percent through a tidal period. The symbols on the left panel indicate minimal and maximal C_D values, with corresponding times drawn on the tidal velocity diagram in the right panel. Maximal C_D results for flow in the southeast direction, roughly down-slope.

Moving from qualitative analysis of the rough time/space dependence requires reference to the "cost function", i.e., the integral misfit between model and observation. We have found that the misfit is reduced by switching from a C_D that is constant in time, to one that has an additional M2 dependence. Fig. 2 shows the result of such an analysis. In the run shown, C_D varies about 20 percent through the M2 tidal cycle. Also notable is the correspondence of the C_D variation with the tidal-flow orientation:

4

C_D is largest when the mid-column tidal flow is to the southeast, and smallest when it is to the northwest. Pending further tests, including a similar study at the other sampling site, this is a tentative result, but it a tantalizing one since it matches the bottom slope, with deep water lying the southeast. A possible explanation might be that C_D increases during down-slope flow because down-slope flow favors the formation of centimeter-scale ripples due to a saltation effect of sediment grains. We are preparing a publication to discuss such issues.

IMPACT/APPLICATIONS

Results of this study will improve the accuracy of coastal-ocean models.

TRANSITIONS

At this stage, our results are not being used outside our respective research groups.

RELATED PROJECTS

N/A

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